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# LOCAL MAGNITUDES AND APPARENT VARIATIONS IN SEISMICITY RATES IN SOUTHERN CALIFORNIA

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## ABSTRACT

**Redetermination of local magnitudes for moderate earthquakes recorded by the Southern California Seismographic Network (SCSN) from 1932 to 1990 has shown that the magnitudes have not been consistently determined over that time period. The amplitudes of ground velocities recorded on Wood - Anderson instruments were systematically overestimated prior to 1944 compared to present reading procedures, leading to a significant overestimation of local magnitudes. In addition, the change from human to computerized estimation of event magnitude from a suite of amplitudes in 1975 led to slightly lower event magnitudes for the time after 1975 compared to the time before. These changes contribute to an apparently higher rate of seismicity in the 1930s and 1940s than later in the catalog, which had been interpreted as a decrease in seismicity rate after the 1952 Kern County ($M_w$ 7.5) earthquake. Wood - Anderson amplitudes have been reread and consistent magnitudes recalculated using uniform procedures for all earthquakes with a catalog magnitude of 4.5 and greater within the SCSN from 1932 to 1943 and those with a catalog magnitude of 4.8 and greater from 1944 to 1990 so as to create a complete list of all earthquakes with a modern local magnitude of 5.0 or greater. Using these new magnitudes, we find that the rate of $M_L$ 5.0 and greater earthquakes in southern California over this 59-year period to be Poissonian, with no changes in rate significant above the 90% level. From this rate, in any 30-year period, the Poissonian probability of a $M \geqq 6$ earthquake is 99.7%, the probability of an $M \geqq 7$ earthquake is 65%, and the probability of an $M \geqq 8$ event is 18%.**

## INTRODUCTION

Several researchers have suggested that the rate of seismic activity in southern California has varied considerably over the last century (Hutton *et al.*, 1979; Raleigh *et al.*, 1982; Sykes and Jaume, 1990). In particular, they proposed that the rate of moderate earthquakes was significantly higher before the region's largest earthquake, the 1952 Kern County event ($M_w$ 7.5), than afterwards. Such a correlation between the occurrence of moderate and large earthquakes, if true, could be an important piece of evidence in the study of the generation of large earthquakes. However, several factors and processing artifacts can lead to apparent changes in seismicity. We have therefore used the data available from the Southern California Seismographic Network (SCSN) operated by Caltech and the USGS to reexamine the rate of moderate earthquakes ($M_L \geqq 5.0$) in southern California to determine if a significant change in rate of seismicity did occur.

Variations in the rate of seismic activity have been documented in several regions and variously attributed to precursory activity to major earthquakes (e.g., Wyss and Burford, 1985; Wyss and Habermann, 1988; Wyss and Fu, 1989; Sykes and Jaume, 1990), artifacts such as changes in methods for determining magnitudes (e.g., Habermann, 1987), and unknown causes (e.g., Heaton, 1987; Reasenberg and Matthews, 1988). Habermann (1982, 1987) has shown that apparent changes in the rate of seismicity can be human-made changes, caused primarily by variations in the methods used for determining magnitude. Magnitudes of moderate earthquakes in southern California have always been local magnitudes ($M_L$) (Richter, 1935, 1958; Hutton and Boore, 1987), but this does not guarantee stability of the scale. "Drift" in the magnitude scale might be caused by (1) changes in the Wood–Anderson torsion seismometers, upon which the local magnitude scale is based; (2) changes in the group of stations in operation with time; (3) changes in procedures and standards of measuring amplitudes; or (4) changes in statistical procedures used in selecting the final estimate of the magnitude, based on a distribution of station and component estimates of magnitude. Hutton *et al.* (1979) reread and recomputed magnitudes for a few random earthquakes in the early part of the catalog, to determine if any such problems were apparent. They saw no large systematic bias; however, the sample was small.

Our goal in this study was to produce a catalog of mainshocks complete above $M_L$ 5.0 in which the magnitudes were calculated in a consistent manner over the last 60 years and then determine from this data set if a significant change in rate of earthquakes had occurred. We therefore re-examined the magnitudes for all mainshocks of $M_L$ 4.8 and larger in the southern California catalog (Hileman *et al.*, 1973; Friedman *et al.*, 1976; Fuis *et al.*, 1977; Hutton *et al.*, 1985) to be able to recognize earthquakes that might have been assigned too small a magnitude. Because amplitudes appear to have been overestimated before 1943 compared to present practice, all earthquakes with a local magnitude of 4.5 or greater were checked for 1932 to 1943. To be sure of completeness, the catalog was restricted to earthquakes in the central part of the SCSN as shown in Figure 1. We reread the amplitudes on original records for earthquakes before 1970 and recomputed magnitudes of all events from 1932 to 1990. We then used this new data to form a complete catalog with stable magnitudes for mainshocks of magnitude 5.0 and greater.

Reasenberg and Matthews (1988) have shown that apparently large changes in the rate of seismicity may not be statistically significant. We have used the methods of Matthews and Reasenberg (1988) to examine the significance of changes in this stable southern California catalog. We found that no significant change in the rate of moderate earthquakes has occurred in southern California in the last 59 years. A bias towards overestimating the magnitude in the early part of the catalog (1932 to 1943) contributed much of the apparent increased rate previously reported for the period before the Kern County earthquake. We did find increased activity for the period from 1938 to 1946, but, because of the small number of earthquakes above magnitude 5, the increase is not statistically significant.

## Local Magnitudes

Procedures for determining local magnitudes in southern California have evolved with time. In light of possible changes in procedure, we have reanalyzed the data available from the SCSN to compile a complete catalog of moderate earthquakes (excluding aftershocks) with consistently determined magnitudes.

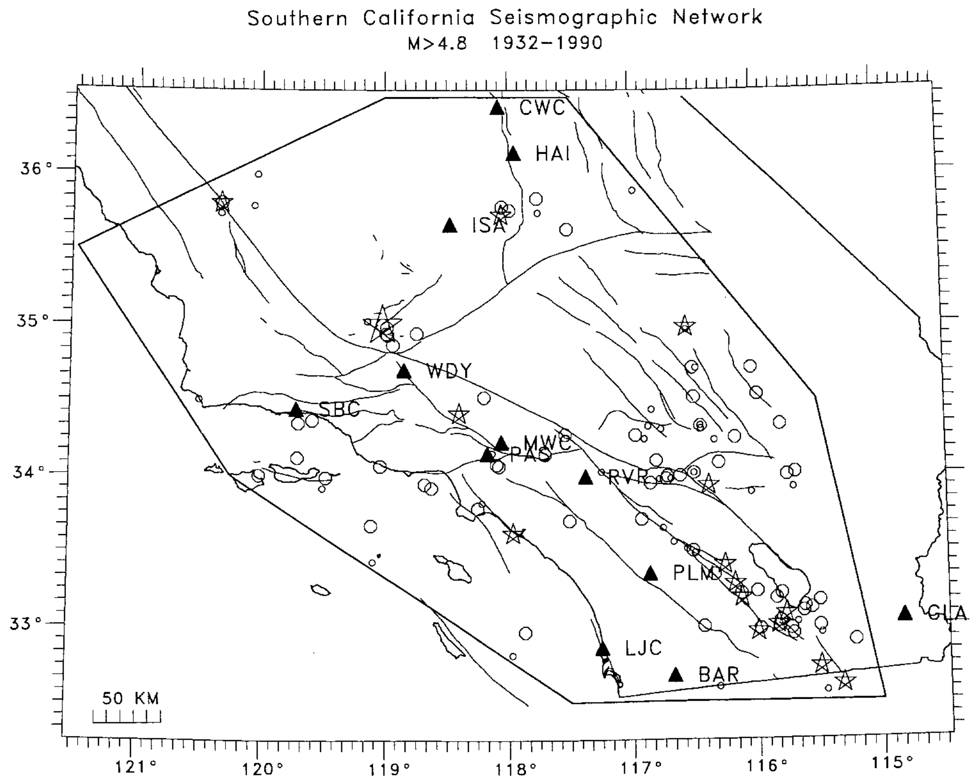


FIG. 1. Map of southern California showing the epicenters of earthquakes relocated in this study, events with a catalog magnitude of 4.8 or greater located within the central part of the Southern California Seismic Network (SCSN), as shown by the polygon. Earthquakes of $M$ 4.8 to 4.9 are shown by small circles, $M$ 5.0 to 5.9 by large circles, and $M \geq 6.0$ by stars. Wood-Anderson stations in the SCSN are shown by triangles.

*Current Procedures*

Local magnitudes are determined from the presently operating Wood–Anderson instruments listed in Table 1 (Fig. 1). The amplitude of ground motion at each station is measured to the nearest half millimeter as half of the peak-to-peak distance on the largest single swing of the $S$ wave. Occasionally, when the seismogram is only partly readable, a "half peak-to-peak" reading will be made without any assurance that the upper and lower peaks belong to the same wave. An estimate of the magnitude is made from each station component using a distance correction from the standard $A_0$ table (Richter, 1958) and individual station corrections determined for each station. Individual estimates can vary widely both from path and source effects. The median (the midpoint of the magnitude estimates) is used as the magnitude of the earthquake in order to minimize the influence of widely divergent estimates.

*Potential Problems*

Differences could arise between magnitudes assigned to earthquakes in previous years and current practice because of (1) changes in stations, (2) changes in how the amplitudes are read, or (3) changes in the statistical methods for assigning magnitude from a suite of station and component readings. The Wood–Anderson instruments themselves have remained unchanged, except for

TABLE 1

WOOD–ANDERSON STATIONS IN THE SOUTHERN CALIFORNIA SEISMIC NETWORK, 1932–1990

| Station Name | Code | Location | | Installed (m/d/y) | Discontinued (m/d/y) |
|---|---|---|---|---|---|
| Barrett Dam | BAR | 32° 40.80 N | 116° 40.30 W | 01/17/52 | 04/05/83 |
| Cottonwood | CWC | 36° 26.35 N | 118° 04.68 W | 10/13/65 | Present |
| Glamis | GLA* | 33° 3.10 N | 114° 49.60 W | 12/20/60 | Present |
| Haiwee Dam | HAI | 36° 8.20 N | 117° 56.80 W | 09/11/29 | 10/27/65 |
| Isabella | ISA* | 35° 39.80 N | 118° 28.40 W | 01/14/62 | Present |
| La Jolla | LJC | 32° 51.80 N | 117° 15.20 W | 05/04/27 | 07/30/52 |
| Mount Wilson | MWC | 34° 13.40 N | 118° 3.50 W | 04/23/28 | 01/23/51 |
| Pasadena | PAS | 34° 8.95 N | 118° 10.29 W | 03/17/27 | Present |
| Palomar Mtn. | PLM | 33° 21.20 N | 116° 51.70 W | 09/07/39 | Present |
| Riverside | RVR | 33° 59.60 N | 117° 22.50 W | 10/19/26 | Present |
| Santa Barbara | SBC | 34° 26.50 N | 119° 42.80 W | 05/10/27 | Present |
| Tinemaha | TIN | 37° 3.30 N | 118° 13.70 W | 09/04/29 | Present |
| Woody | WDY | 34° 42.00 N | 118° 50.60 W | 08/05/52 | 08/27/70 |

*GLA and ISA have electronically simulated Wood–Anderson responses.

Since 1970, PAS, CWC, RVR, and SBC have also operated 100 X Wood–Anderson instruments.

repairs and overhauls, since the beginning of the catalog. Although the possibility has been raised that the stated magnification of 2800 is incorrect (Hutton and Boore, 1987; Urhammer and Collins, 1990), the same physical instruments have been used since the beginning of the catalog, and, as far as we know, their magnification has remained the same throughout. Because the local magnitude scale is defined by the Wood–Anderson instruments, the actual amplification does not matter as long as the real instruments are used and they do not drift with time. We have no evidence of significant drift in the southern California stations (minor drift has been reported for Berkeley stations; Urhammer and Collins, 1990); a comparison of stations corrections determined before and after station overhauls has shown no variation. Only four technicians have been responsible for maintenance of the Wood–Andersons over the past 60 years.

In 1968, low-gain Wood–Andersons were installed at four stations. These instruments have a nominal amplification of 4 or 100, as compared to the nominal amplification of 2800 for the original Wood–Andersons. Station corrections for these low-gain instruments are determined empirically. Therefore, the magnitude estimates from these instruments should be compatible with the original instruments even if the actual amplification of these and the original Wood–Anderson instruments are not as advertised. However two potential problems arise with the use of these instruments. First, the calibration of the low-gain instruments is based on relatively few earthquakes and is therefore less reliable. Second, and more significantly, Hutton and Boore (1987) showed that the distance correction developed for local magnitudes by Richter is incorrect, so that magnitudes estimated from nearby stations are smaller than magnitudes estimated from more distant stations. The low-gain stations preferentially record nearby earthquakes and thus tend to underestimate the magnitudes compared to regular Wood–Anderson instruments. We have therefore not used the low-gain instruments for determining magnitudes in this study.

The geographic distribution of the Wood–Anderson stations used for determining magnitudes has changed with time, which could produce temporal variations in the magnitude estimates. Table 1 gives the dates of operation for Wood–Anderson seismometers in southern California. Four sites, out of a total of 13, operated throughout the whole time period in question. The station residuals of these four stations do not show a drift with time, suggesting that changes in the geographic distribution of stations with time is not a serious factor.

Procedures for reading amplitudes have been handed down verbally from analyst to analyst and have probably changed with time. The current SCSN staff read the peak-to-peak distance on the largest single swing of the *S* wave and use half of that number. As far as we can tell, readings at Caltech have always been restricted to the largest single swing. Although Richter (1958) states that magnitude was determined from the largest amplitude in any phase, Gutenberg and Richter (1956) say to ignore any *P* phase, in agreement with present practice. This seems to have been the practice for a long time.

Prior to the computerization of the SCSN in 1977, the procedure for determining the actual earthquake magnitude from a suite of readings was somewhat ill defined. Richter (1958) states that a magnitude is computed for each Wood–Anderson instrument, using a station correction determined from past experience, and the earthquake magnitude is the mean of these estimates. The current, computerized procedure is to use the median of the magnitude estimates. In the past, however, the local magnitude appears to have been chosen from the list of station magnitudes based partly on the subjective opinion of an analyst considering the reliability of individual stations. Prior to 1944, most magnitudes were estimated only to the nearest half unit, rather than to the nearest tenth unit, which is the current practice. It is clear, therefore, that the variety of magnitude computation procedures could have biased the catalog magnitudes.

*Redetermination of Magnitude*

The variations in procedures used at different times by the SCSN demonstrates that the best possible magnitudes can only be achieved by going back to the original seismograms of the SCSN. We have done this for all earthquakes with catalog magnitudes above $M_L$ 4.8 (Fig. 1), so as to be complete for accurate magnitudes of $M_L$ 5.0. The two major possible sources of error in the catalog magnitudes are (1) changes in procedures for reading amplitudes and (2) changes in procedures for determining the earthquake magnitude from the estimates of magnitude from each station.

To assess the first problem, amplitudes were reread from the original seismograms for the earthquakes prior to 1970. The amplitudes used in the catalog since 1970 were read by analysts now employed or their immediate predecessors so that the procedures they used are known to be the same as present practice. Spot checks of post-1970 seismograms have found no discrepancies. A few events were too large to be recorded clearly on the Wood–Andersons. The catalog magnitude was retained for one event in 1949 whose seismograms were missing from the archive. Another event, at 05:36 GMT on 16 September 1963, was not found on the seismograms for that date; the catalog entry probably refers to an event at the same time and date in 1962. This event was removed from the catalog.

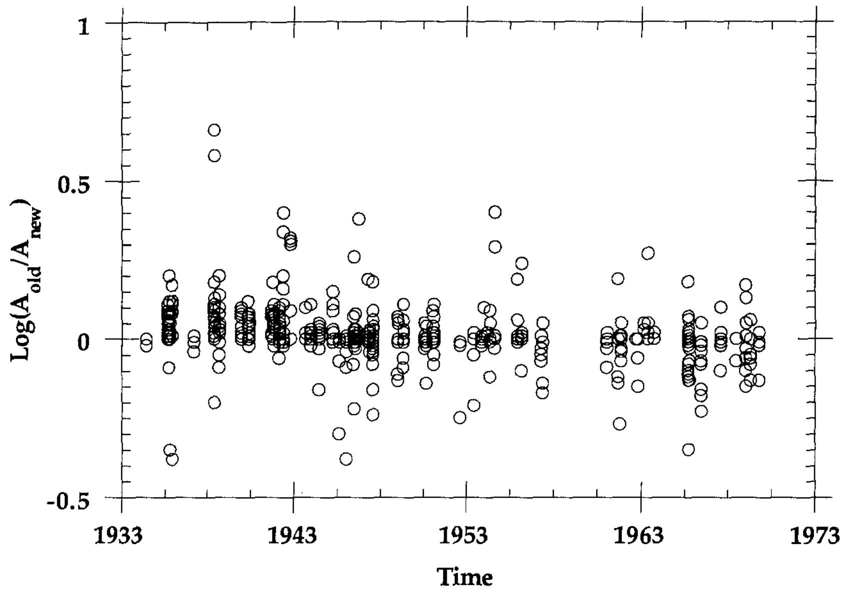


FIG. 2. The difference in the logarithms of the old archived and newly reread amplitudes plotted as a function of time for $M \geqq 4.8$ earthquakes in the Caltech catalog 1932 to 1970.

Figure 2 compares the archived amplitude readings with those read for this paper. Amplitudes read prior to 1944 appear to be overestimated. The archived amplitude readings from 1932 to 1943 are, on average, 15% larger than the amplitudes read here. Several events had amplitudes misread by a large enough amount to change the resultant magnitude by 0.6. Why the accuracy of the amplitude readings improves in 1944 is not clear, but this is the time when the routine procedure was changed to compute magnitudes to the nearest 0.1 unit, rather than the nearest 0.5 unit. We can speculate that the procedural change inspired greater care in making the amplitude readings. Another possibility is that maximum trace amplitudes (as opposed to the largest single swing) were read before 1943, but we have no evidence that this is the case. The period from 1944 to 1969 shows no systematic bias in the amplitudes compared to the new readings, although the scatter is large.

To assess the effect of the second problem, changes in procedures for magnitude determination, the magnitudes were recalculated for all events from 1932 to 1990, using the modern procedure and the newly reread amplitudes. Wood–Anderson instruments were operated at Mount Wilson (MWC), La Jolla (LJC), and Haiwee Reservoir (HAI) in the early days of the Network. However, current procedure does not contain station magnitude corrections for them. Our magnitude recomputations, therefore, took a two-step path. First, we calculated all the local magnitudes using our routine station magnitude corrections. Then we determined new corrections for all stations, including MWC, LJC, and HAI, based on the residuals. New and old station corrections are listed in Table 2. Considering the usual level of scatter in local magnitude determinations, the newly determined corrections are close to the corrections used in current procedure.

TABLE 2
STATION MAGNITUDE CORRECTIONS

| Station | Component | Richter | In Use | New |
|---|---|---|---|---|
| BAR | N | −0.2 | 0.0 | 0.1 |
| CWC | E | | 0.0 | 0.25 |
| | N | | 0.0 | 0.3 |
| GLA | E | | −0.2 | −0.15 |
| | N | | −0.2 | 0.1 |
| HAI | E | 0.0 | | −0.05 |
| | N | 0.0 | | −0.05 |
| ISA | E | | 0.2 | 0.2 |
| | N | | 0.2 | 0.3 |
| LJC | E | | | −0.1 |
| | N | | | −0.15 |
| MWC | E | | | 0.05 |
| | N | | | 0.1 |
| PAS | E | 0.2 | 0.1 | 0.2 |
| | N | 0.2 | 0.1 | 0.15 |
| PLM | E | | 0.0 | 0.0 |
| | N | | 0.0 | 0.0 |
| RVR | E | 0.2 | 0.1 | 0.25 |
| | N | 0.2 | 0.1 | 0.3 |
| SBC | E | −0.2 | −0.1 | −0.2 |
| | N | −0.2 | −0.1 | −0.2 |
| TIN | E | −0.2 | −0.2 | −0.4 |
| | N | −0.2 | −0.2 | −0.4 |
| WDY | E | −0.1 | | |

### *New Magnitudes*

Using these corrections and the current procedures outlined above, we recomputed the magnitudes for the events (Table 3). Many of the largest events were too large for amplitudes to be recorded on scale on at least three Wood–Anderson instruments. The source of catalog magnitudes for these large events is, in several cases, unclear. For the 1933 Long Beach earthquake, the catalog local magnitude was estimated by comparison with the coda for a smaller aftershock for which the local magnitude could be determined (Richter, 1935). This may also be the case for the 1940 Imperial Valley and 1948 Desert Hot Springs events. In addition, because local magnitudes are determined from the higher frequencies, they probably underestimate the energy released in larger earthquakes (Hanks and Kanamori, 1979). We have therefore used moment ($M_w$) magnitudes for the earthquakes not recorded on at least three Wood–Anderson instruments as noted in Table 3. This occurs at about $M$ 6.

A comparison of the old and new magnitudes reveal a systematic bias with time of the local magnitude in the SCSN catalog. Figure 3 shows the difference between the magnitudes determined here and those in the catalog as a function of time. The catalog history seems to be divided into three periods: 1932 to 1943, 1944 to 1976, and 1977 to 1990. In the first, magnitudes in the catalog were only estimated to the nearest 0.5 units, so that the differences between old and new magnitudes are often quite large. In addition, the catalog magnitudes are clearly larger on average, as would be expected from the overestimation of amplitudes seen in Figure 2. The average difference between old and new

TABLE 3

EARTHQUAKES $M_L \geqq 4.8$ FROM THE CALTECH CATALOG

| Date | Time (GMT) | Latitude | Longitude | $M_L$ (Old) | $M_L$ New | Reference |
|---|---|---|---|---|---|---|
| 33/03/11 | 0154 7.80 | 33° 37.00 | 117° 58.00 | 6.3 | *6.4**† | Hauksson and Gross (1991) |
| 34/06/08 | 0447 0.00 | 35° 48.00 | 120° 20.00 | 6.0 | 6.1† | |
| 35/09/08 | 1703 0.00 | 32° 54.00 | 115° 13.00 | 5.0 | 4.4 | |
| 35/10/11 | 1406 0.00 | 32° 54.00 | 115° 13.00 | 5.0 | 4.6 | |
| 35/10/24 | 1448 7.60 | 34° 6.00 | 116° 48.00 | 5.1 | 5.1† | |
| 35/12/20 | 0745 0.00 | 33° 10.00 | 115° 30.00 | 5.0 | 5.2† | |
| 37/03/25 | 1649 1.83 | 33° 24.51 | 116° 15.69 | 6.0 | 6.0† | |
| 38/05/31 | 0834 55.41 | 33° 41.93 | 117° 30.64 | 5.5 | 5.2† | |
| 38/06/06 | 0242 0.00 | 32° 54.00 | 115° 13.00 | 5.0 | 4.8 | |
| 38/09/17 | 1423 4.09 | 35° 37.84 | 117° 30.81 | 5.0 | 4.7 | |
| 39/12/28 | 1215 38.00 | 35° 48.00 | 120° 20.00 | 5.0 | 4.9 | |
| 40/05/18 | 0503 58.50 | 34° 5.00 | 116° 18.00 | 5.4 | 5.3† | |
| 40/05/19 | 0436 40.90 | 32° 44.00 | 115° 30.00 | (6.7)* | *6.9**† | Ellsworth (1990) |
| 40/06/04 | 1035 8.30 | 33° 0.00 | 116° 26.00 | 5.1 | 4.9 | |
| 41/07/01 | 0750 54.80 | 34° 22.00 | 119° 35.00 | 5.9 | 5.5† | |
| 41/09/21 | 1953 7.20 | 34° 52.00 | 118° 56.00 | 5.2 | 5.1† | |
| 41/10/22 | 0657 18.50 | 33° 49.00 | 118° 13.00 | 4.9 | 4.8 | |
| 41/11/14 | 0841 36.30 | 33° 47.00 | 118° 15.00 | 5.4 | 4.8 | |
| 42/03/03 | 0103 24.00 | 34° 0.00 | 115° 45.00 | 5.0 | 5.0† | |
| 42/05/23 | 1547 29.00 | 32° 59.00 | 115° 59.00 | 5.0 | 5.1† | |
| 42/10/21 | 1622 13.00 | 32° 58.00 | 116° 0.00 | 6.5 | *6.6**† | Ellsworth (1990) |
| 43/08/29 | 0345 13.00 | 34° 16.00 | 116° 58.00 | 5.5 | 5.3† | |
| 43/12/22 | 1550 28.00 | 34° 20.00 | 115° 48.00 | 5.5 | 5.3† | |
| 44/06/12 | 1045 34.66 | 33° 58.57 | 116° 43.24 | 5.1 | 5.0† | |
| 44/06/12 | 1116 35.97 | 33° 59.67 | 116° 42.70 | 5.3 | 5.2† | |
| 45/03/20 | 2155 7.00 | 34° 15.00 | 116° 10.00 | 5.0 | 4.9 | |
| 45/04/01 | 2343 42.00 | 34° 0.00 | 120° 1.00 | 5.4 | 5.1† | |
| 45/08/15 | 1756 24.00 | 33° 13.00 | 116° 8.00 | 5.7 | 5.7† | |
| 46/01/08 | 1854 18.00 | 33° 0.00 | 115° 50.00 | 5.4 | 5.4† | |
| 46/03/15 | 1321 0.90 | 35° 45.20 | 117° 59.18 | 5.2 | 5.5 | |
| 46/03/15 | 1349 35.90 | 35° 43.51 | 118° 3.28 | 6.3 | *6.0**† | Ellsworth (1990) |
| 46/06/04 | 1205 24.00 | 33° 55.00 | 115° 42.00 | 4.8 | 4.7 | |
| 46/06/15 | 1946 53.00 | 32° 36.00 | 116° 19.00 | 4.8 | 4.7 | |
| 46/07/18 | 1427 58.00 | 34° 32.00 | 115° 59.00 | 5.6 | 5.5† | |
| 46/09/28 | 0719 9.00 | 33° 57.00 | 116° 51.00 | 5.0 | 4.8 | |
| 47/04/10 | 1558 6.00 | 34° 59.00 | 116° 33.00 | 6.2 | *6.5**† | Doser (1990) |
| 47/05/11 | 0506 20.00 | 34° 14.00 | 116° 20.00 | 4.9 | 4.6 | |
| 47/07/24 | 2210 46.00 | 34° 1.00 | 116° 30.00 | 5.5 | 5.3† | |
| 47/07/24 | 2254 26.00 | 34° 1.00 | 116° 30.00 | 4.9 | 4.7 | |
| 47/07/25 | 0046 31.00 | 34° 1.00 | 116° 30.00 | 5.0 | 4.8 | |
| 47/07/25 | 0619 49.00 | 34° 1.00 | 116° 30.00 | 5.2 | 5.2 | |
| 47/07/26 | 0249 41.00 | 34° 1.00 | 116° 30.00 | 5.1 | 4.9 | |
| 48/12/04 | 2343 17.00 | 33° 56.00 | 116° 23.00 | 6.5 | *6.0**† | Hanks *et al.* (1975) |
| 49/01/03 | 1343 40.00 | 34° 58.00 | 116° 33.00 | 4.8 | 4.5 | |
| 49/05/02 | 1125 47.00 | 34° 1.00 | 115° 41.00 | 5.9 | 5.8† | |
| 49/08/27 | 1451 46.00 | 34° 30.00 | 120° 30.00 | 4.9 | | Records missing |
| 50/07/28 | 1750 48.00 | 33° 7.00 | 115° 34.00 | 5.4 | 5.4 | |
| 50/07/29 | 1436 32.00 | 33° 7.00 | 115° 34.00 | 5.5 | 5.5 | |
| 50/09/05 | 1919 56.00 | 33° 39.00 | 116° 45.00 | 4.8 | 4.7 | |
| 51/01/24 | 0717 2.60 | 32° 59.00 | 115° 44.00 | 5.6 | 5.8† | |
| 51/02/15 | 1047 59.00 | 33° 29.00 | 116° 30.00 | 4.8 | 4.8 | |
| 51/02/15 | 1049 57.00 | 33° 29.00 | 116° 30.00 | 4.8 | 4.6 | |

TABLE 3

*Continued*

| Date | Time (GMT) | Latitude | Longitude | $M_L$ (Old) | $M_L$ New | Reference |
|---|---|---|---|---|---|---|
| 52/07/21 | 1152 14.00 | 35° 0.00 | 119° 1.00 | (7.7)* | *7.5**† | Hanks *et al.* (1975) |
| 52/08/23 | 1009 7.15 | 34° 31.16 | 118° 11.89 | 5.0 | 5.1† | |
| 53/06/14 | 0417 29.90 | 32° 57.00 | 115° 43.00 | 5.5 | 5.5† | |
| 53/11/24 | 0546 6.00 | 35° 53.00 | 116° 58.00 | 4.9 | 4.7 | |
| 54/01/12 | 2333 49.00 | 35° 0.00 | 119° 1.00 | 5.9 | 5.6 | |
| 54/03/19 | 0954 29.00 | 33° 17.00 | 116° 11.00 | 6.2 | *6.4**† | Ellsworth (1990) |
| 54/05/23 | 2352 43.00 | 34° 59.00 | 118° 59.00 | 5.1 | 5.1 | |
| 54/08/26 | 1348 3.00 | 33° 55.00 | 119° 30.00 | 4.8 | 4.7 | |
| 55/12/17 | 0607 29.00 | 33° 0.00 | 115° 30.00 | 5.4 | 5.2† | |
| 56/03/16 | 2029 33.65 | 34° 18.36 | 116° 45.55 | 4.8 | 4.8 | |
| 57/04/25 | 2157 38.70 | 33° 12.99 | 115° 48.50 | 5.2 | 5.2† | |
| 57/04/25 | 2224 12.00 | 33° 11.00 | 115° 51.00 | 5.1 | 5.1 | |
| 57/05/26 | 1559 33.64 | 33° 13.88 | 116° 0.27 | 5.0 | 5.0† | |
| 61/01/28 | 0812 46.18 | 35° 46.69 | 118° 2.92 | 5.3 | 5.3† | |
| 61/09/12 | 1918 45.55 | 32° 34.02 | 115° 27.15 | 4.8 | 4.9 | |
| 61/10/19 | 0509 43.92 | 35° 49.89 | 117° 45.67 | 5.2 | 5.4† | |
| 61/11/15 | 0538 55.49 | 34° 56.47 | 118° 59.20 | 5.0 | 4.9 | |
| 62/09/16 | 0536 16.01 | 35° 45.26 | 118° 2.64 | 4.9 | 5.0† | |
| 62/10/29 | 0242 53.89 | 34° 19.52 | 116° 51.90 | 4.8 | 5.0† | |
| 63/03/01 | 0025 57.86 | 34° 55.95 | 118° 58.55 | 5.0 | 4.5 | |
| 63/05/23 | 1553 1.82 | 33° 1.63 | 115° 40.87 | 4.8 | 4.8 | |
| 63/09/23 | 1441 52.58 | 33° 42.61 | 116° 55.50 | 5.0 | 5.1† | |
| 65/09/19 | 1542 7.84 | 35° 59.22 | 120° 2.34 | 4.8 | 4.6 | |
| 65/09/25 | 1743 44.12 | 34° 42.75 | 116° 30.16 | 5.2 | 5.2† | |
| 65/09/25 | 1748 2.41 | 34° 42.66 | 116° 28.54 | 4.9 | 4.9 | |
| 65/09/26 | 0700 1.75 | 34° 42.67 | 116° 1.61 | 5.0 | 5.1 | |
| 65/10/17 | 0945 18.99 | 33° 58.55 | 116° 46.48 | 4.9 | 4.9 | |
| 66/06/29 | 1953 29.49 | 35° 46.86 | 120° 3.96 | 4.8 | 4.7 | |
| 67/08/12 | 1857 41.53 | 35° 43.87 | 120° 20.22 | 4.8 | 4.2 | |
| 68/04/09 | 0228 59.06 | 33° 11.40 | 116° 7.72 | 6.4 | *6.5**† | Ellsworth (1990) |
| 68/07/05 | 0045 17.22 | 34° 7.06 | 119° 42.15 | 5.2 | 5.3† | |
| 69/01/23 | 2301 0.98 | 33° 53.21 | 116° 2.42 | 4.8 | 5.0† | |
| 69/04/28 | 2320 42.87 | 33° 20.60 | 116° 20.78 | 5.8 | 5.8† | |
| 69/10/31 | 1039 28.96 | 33° 25.79 | 119° 5.77 | 4.8 | 4.7 | |
| 70/09/12 | 1430 52.98 | 34° 16.19 | 117° 32.40 | 5.4 | 5.2† | |
| 71/02/09 | 1400 41.83 | 34° 24.67 | 118° 24.04 | *6.6** | *6.6**† | Heaton (1982) |
| 71/09/30 | 2246 11.30 | 33° 2.01 | 115° 49.24 | 5.1 | 5.0† | |
| 73/02/21 | 1445 57.30 | 34° 3.89 | 119° 2.10 | 5.9 | *5.3**† | Ellsworth *et al.* (1973) |
| 73/07/14 | 0800 20.06 | 34° 26.18 | 116° 50.03 | 4.8 | 4.6 | |
| 73/08/06 | 2329 16.97 | 33° 59.16 | 119° 28.52 | 5.0 | 5.0† | |
| 75/01/12 | 2122 15.04 | 32° 48.91 | 117° 58.46 | 4.8 | 4.7 | |
| 75/01/23 | 1702 29.43 | 32° 57.11 | 115° 29.38 | 4.8 | 4.8 | |
| 75/06/01 | 0138 49.23 | 34° 30.94 | 116° 29.73 | 5.2 | 5.0† | |
| 75/08/02 | 0014 7.70 | 33° 30.78 | 116° 33.55 | 4.8 | 4.8 | |
| 76/11/04 | 1041 37.54 | 33° 7.89 | 115° 37.40 | 5.1 | 5.0† | |
| 78/08/13 | 2254 53.42 | 34° 20.82 | 119° 41.76 | 5.1 | 5.1† | |
| 79/01/01 | 2314 38.94 | 33° 56.66 | 118° 40.88 | 5.0 | 5.2† | |
| 79/03/15 | 2017 49.89 | 34° 18.56 | 116° 26.42 | 4.9 | 4.9 | |
| 79/03/15 | 2107 16.53 | 34° 19.64 | 116° 26.69 | 5.2 | 5.3† | |
| 79/03/15 | 2307 58.17 | 34° 19.79 | 116° 26.57 | 4.8 | 4.8 | |
| 79/06/30 | 0034 11.64 | 34° 14.56 | 116° 53.75 | 4.9 | 4.7 | |

TABLE 3

*Continued*

| Date | Time (GMT) | Latitude | Longitude | $M_L$ (Old) | $M_L$ New | Reference |
|---|---|---|---|---|---|---|
| 79/10/15 | 2316 53.44 | 32° 36.82 | 115° 19.09 | 6.6 | *6.4**† | Hartzell and Heaton (1983) |
| 80/02/25 | 1047 38.53 | 33° 30.06 | 116° 30.75 | 5.5 | 5.5† | |
| 81/04/26 | 1209 28.41 | 33° 5.91 | 115° 37.90 | 5.7 | 5.7† | |
| 81/09/04 | 1550 50.33 | 33° 40.26 | 119° 6.67 | 5.3 | 5.5† | |
| 81/11/10 | 2234 35.43 | 35° 1.44 | 119° 8.31 | 4.8 | 4.8 | |
| 82/06/15 | 2349 21.32 | 33° 33.49 | 116° 40.03 | 4.8 | 4.8 | |
| 82/10/01 | 1429 1.63 | 35° 44.22 | 117° 45.13 | 4.9 | 4.9 | |
| 85/10/02 | 2344 12.45 | 34° 1.40 | 117° 14.71 | 4.8 | 4.8 | |
| 86/07/08 | 0920 44.56 | 33° 59.95 | 116° 36.51 | 5.6 | 5.6† | |
| 86/07/13 | 1347 8.22 | 32° 57.96 | 117° 52.32 | 5.4 | 5.4† | |
| 87/10/01 | 1442 20.02 | 34° 3.68 | 118° 4.71 | 5.9 | *5.9**† | Hartzell and Iida (1990) |
| 87/10/04 | 1059 38.19 | 34° 4.42 | 118° 5.88 | 5.3 | 5.3 | |
| 87/11/24 | 0154 14.51 | 33° 4.95 | 115° 46.51 | (6.2)* | *6.2** | Sipkin (1989) |
| 87/11/24 | 1315 56.46 | 33° 0.76 | 115° 50.30 | (6.6)* | *6.6**† | Sipkin (1989) |
| 88/06/10 | 2306 43.05 | 34° 56.58 | 118° 44.56 | 5.4 | 5.4† | |
| 88/12/03 | 1138 26.44 | 34° 8.93 | 118° 8.08 | 4.9 | 5.0† | |
| 88/12/16 | 0553 5.00 | 33° 58.73 | 116° 40.88 | 4.8 | 4.9 | |
| 89/01/19 | 0653 28.84 | 33° 55.12 | 118° 37.64 | 5.0 | 5.0† | |
| 90/02/28 | 2343 36.70 | 34° 8.29 | 117° 42.17 | 5.2 | 5.3† | |

*Surface wave (in parentheses) or moment (italicized) magnitudes. When the earthquake was too big to determine a local magnitude, surface magnitudes were sometimes put in the catalog. For new magnitudes, if three Wood–Anderson amplitudes could not be found on scale, $M_W$ was used from the listed source. This generally occurs around $M$ 6.0.

†Earthquakes used as part of the final declustered catalog of $M \geqq 5$ earthquakes.

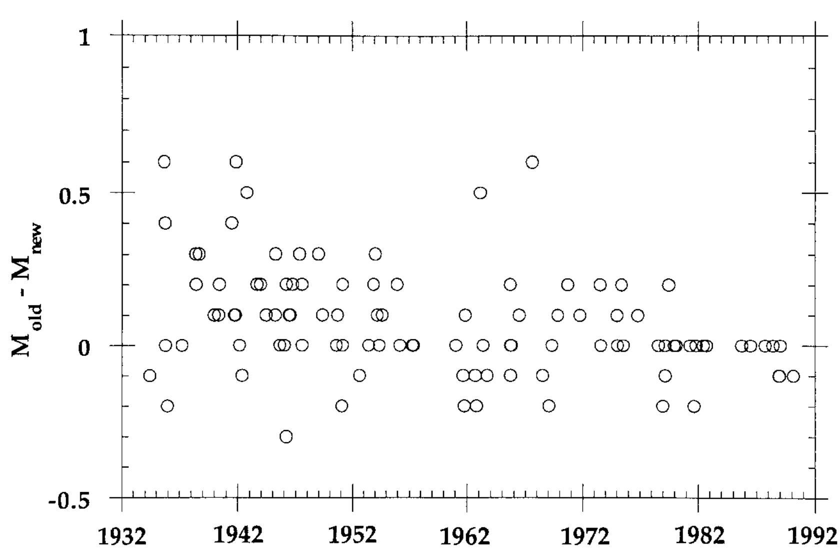


FIG. 3. The difference in the archived magnitude and the magnitude determined in this study as a function of time for earthquakes $M \geqq 4.8$ in the Caltech catalog 1932 to 1990.

magnitude for 21 events from 1932 to 1943 is 0.17 with a standard deviation of 0.22.

The apparent overestimation of magnitudes for the period from 1932 to 1943 could be an artifact of our procedure. If the magnitudes of some events were underestimated by as much as others had been overestimated (0.6), then some of the earthquakes in the catalog with magnitudes below 4.8 not included in this data set could actually be $M \geqq 5.0$ events. We therefore reread the amplitudes and recalculated magnitudes for all non-aftershocks with catalog magnitudes of 4.5 or greater for the period from 1932 to 1943. The largest of these events had a new magnitude of 4.8, so no new $M \geqq 5.0$ events were found. The average difference between old and new magnitudes was 0.1. Thus, it appears that the magnitudes in the catalog for this time period (1932 to 1943) were indeed overestimated compared to modern procedures.

The period from 1944 to 1974 displays a standard deviation of 0.16, almost as large as that for the previous time period. However, the systematic bias is smaller with an average difference of only 0.07. The reason for the large scatter is difficult to ascertain now because the details of the magnitude estimation procedure in use at the time are now obscure. As Figure 2 shows, with the institution of 0.1 unit resolution of magnitudes, amplitudes were, in general, read more carefully, and the systematic overestimation of amplitudes cannot be seen. No systematic difference in old and new amplitudes could be found for this period, so most of the small systematic bias in the event magnitudes must be due to different procedures for determining magnitudes from the amplitudes. In the current procedure, a computer determines the median, whereas, in the earlier time period, an individual made an estimate of the mean including a subjective decision about station reliability. The difference of 0.07 may represent a human tendency to round up.

For 1975 to present, only minor differences arise, as should be expected since current routine procedures were used in computing all the new magnitudes and the amplitudes were not re-read. The estimates for five earthquakes in this time period differ by 0.1 to 0.2 units because we did not use the low gain Wood–Anderson readings (because of problems in the distance correction). The average difference between old and new magnitudes was 0.01 and the standard deviation was 0.09.

## SEISMICITY RATE

Using the catalog magnitudes, Raleigh *et al.* (1982) and Hutton *et al.* (1979, 1991) all proposed that the number of moderate earthquakes in southern California decreased at the time of the region's largest earthquake, the 1952 Kern County Earthquake ($M_w$ 7.5). Hutton *et al.* (1979) noted a decrease from 53 to 36 events per year above $M_L$ 3 3/4 at that time, while Hutton *et al.* (1991) showed that the decrease corresponds to a change from about two to about one sequences per year containing at least one $M_L \geqq 5.0$ event. The artificial variations in catalog magnitudes found here suggest that this rate change could be an artifact. We have examined the proposed rate change using the techniques of Matthews and Reasenberg (1988) to test for statistical significance. We first analyzed the data available to those researchers and the Caltech catalog and then compared this to the results using the newly determined consistent magnitudes.

Matthews and Reasenberg (1988) defined a $\beta$-statistic to analyze the significance of changes in rate of seismicity during some time interval. For a seismic catalog, the $\beta$-statistic can be evaluated for two-dimensional intervals of time from $t$-$\delta$ to $t$ for all possible values of $t$ (interval end time) and $\delta$ (duration of the interval). For a given time interval, $\beta(t, \delta)$ measures the difference in rate of seismicity between the interval and its complement (the rest of the time in the catalog). We have evaluated the intervals with increments of 1 year. In this case, an interval for which the absolute value of $\beta$ is greater than 3.74 has a 10% or less chance of being a random fluctuation in a constant rate Poissonian distribution of earthquakes.

The number of sequences with at least one earthquake of magnitude 5.0 or greater in southern California is plotted versus time in Figure 4 using both the old catalog magnitudes and the newly redetermined magnitudes. The effect of the overestimation of magnitudes in the 1930s and 1940s can be seen in the increasing separation between the two curves during that time. Nine earthquakes previously reported as $M \geqq 5.0$ between 1935 and 1946 were assigned magnitudes below 5.0 in the new catalog. In the 1960s, three earthquakes moved up to the magnitude 5 level and three other events moved below that level with the new magnitudes. Because the new magnitudes do not use the low-gain Wood–Anderson instruments that were used in the catalog, one event in 1988 changed from $M$ 4.9 to 5.0. In total, using the new magnitudes, eight

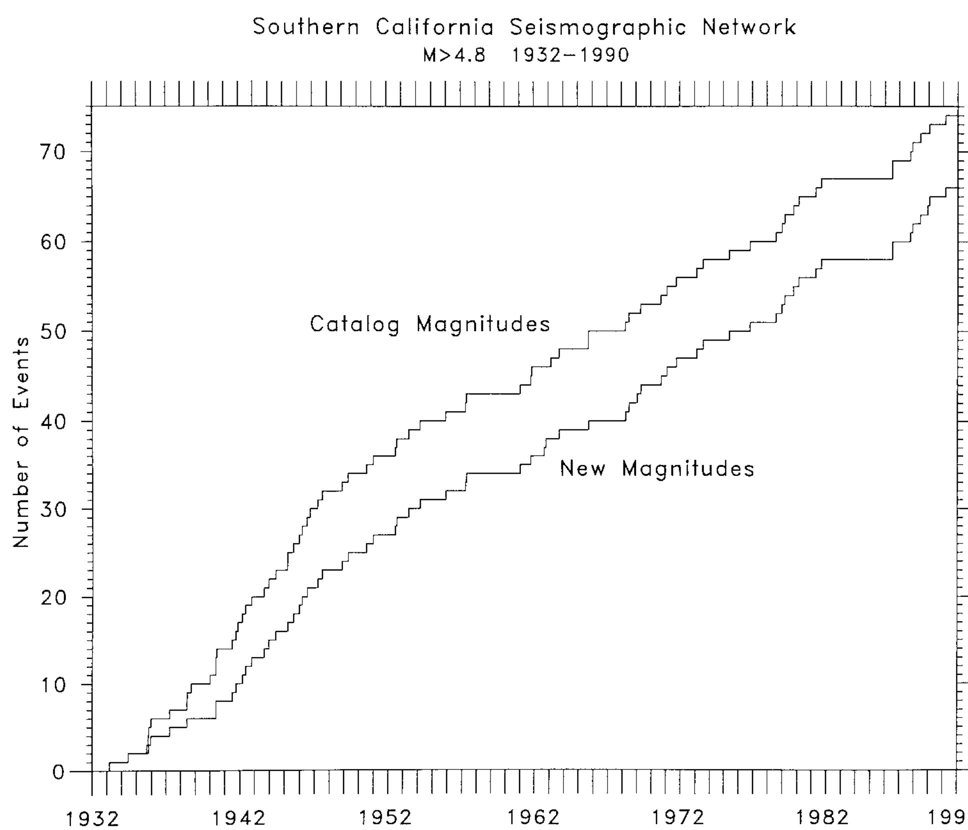


FIG. 4. The cumulative number of earthquakes with a magnitude of 5.0 or greater recorded in central part of the Southern California Seismic Network as a function of time. Two curves are shown, for magnitudes from the Caltech catalog ("Catalog Magnitudes") and magnitudes determined in this study ("New Magnitudes").

fewer events, 66 instead of 74, are assigned magnitudes $M \geqq 5.0$ between 1932 and 1990.

The decade of the 1940s has more earthquakes than the decades since then in both catalogs, but the increase is much less pronounced using the new magnitudes. To assess the significance of this change in rate, the $\beta$-statistic has been evaluated for all intervals in the catalog from 1932 to 1990 (Fig. 5). For comparison, the $\beta$-statistic is evaluated using both the old, catalog magnitudes (Fig. 5a) and the newly determined magnitudes (Fig. 5b). Using the old magnitudes, the increase in rate in the 1940s is statistically significant at the 90% level. This is seen by the region of $\beta \geqq 3.74$ for intervals ending in 1946 that are 8 to 12 years long in Figure 5a. Using the new magnitudes with nine fewer $M \geqq 5.0$ events between 1935 and 1946 (Fig. 5b), the significance of the increase disappears. The largest absolute value of $\beta$ is 2.7 for an 8-year interval ending in 1946.

We conclude that the catalog of $M \geqq 5.0$ earthquakes in southern California over the last 60 years is well represented by a Poissonian distribution and that no significant variation in the rate has occurred. The previously reported increase prior to the 1952 earthquake results from a small, real but insignificant increase from 1940 to 1946 with five events above the average in that time and nine events misassigned too large a magnitude. It is also clear that the rate of earthquakes did not increase in 1978 as reported by Raleigh *et al.* (1982). Several moderate earthquakes occurred between 1978 and 1980, but this was followed by the longest period with no $M \geqq 5.0$ earthquakes (almost 5 years from September 1981 to July 1986), so that the rate from 1978 to 1985 is actually slightly below average.

The magnitude-frequency distribution of the declustered southern California earthquakes from 1932 to 1990 is shown in Figure 6. The $b$-value is $0.74 \pm 0.12$. Declustered catalogs have lower $b$-values than catalogs with foreshocks and aftershocks included because the smaller events of the clusters have been preferentially removed (e.g., Frolich and Davis, 1993). The rate of occurrence of the earthquakes over the last 60 years and the magnitude frequency distribution can be used to estimate the probability of occurrence of earthquakes of various sizes in southern California. The average repeat time, $T$, for different magnitudes can be estimated from the magnitude frequency distribution as shown in Table 4. If the rate of occurrence of an earthquake of $M \geqq M_r$ is $\lambda = 1/T$, then the probability of that earthquake occurring in a time interval, $t$, is $P(t) = 1 - \exp(-\lambda t)$.

The data are dominated by smaller events, so the actual rate of large earthquakes in southern California is not well resolved with only 59 years of data. However, by extrapolating from moderate to large events (as is commonly done in engineering practice), probabilities of large earthquakes can be estimated. The probabilities and 1 $\sigma$ uncertainties in 10 and 30 years of large earthquakes in southern California are listed in Table 4. The probability of an $M \geqq 6$ earthquake somewhere in southern California in the next 30 years is over 99%, the probability of an $M \geqq 7$ in the same time is $65 \pm 14\%$, while the probability of an $M \geqq 8$ event in 30 years is $18 \pm 9\%$.

The Poissonian probabilities in Table 4 can be compared to the conditional probabilities calculated for large earthquakes on the San Andreas fault by the Working Group on California Earthquake Probabilities (1988). They estimated the probability of an $M \geqq 7.5$ to 8.0 earthquake on the southern San Andreas

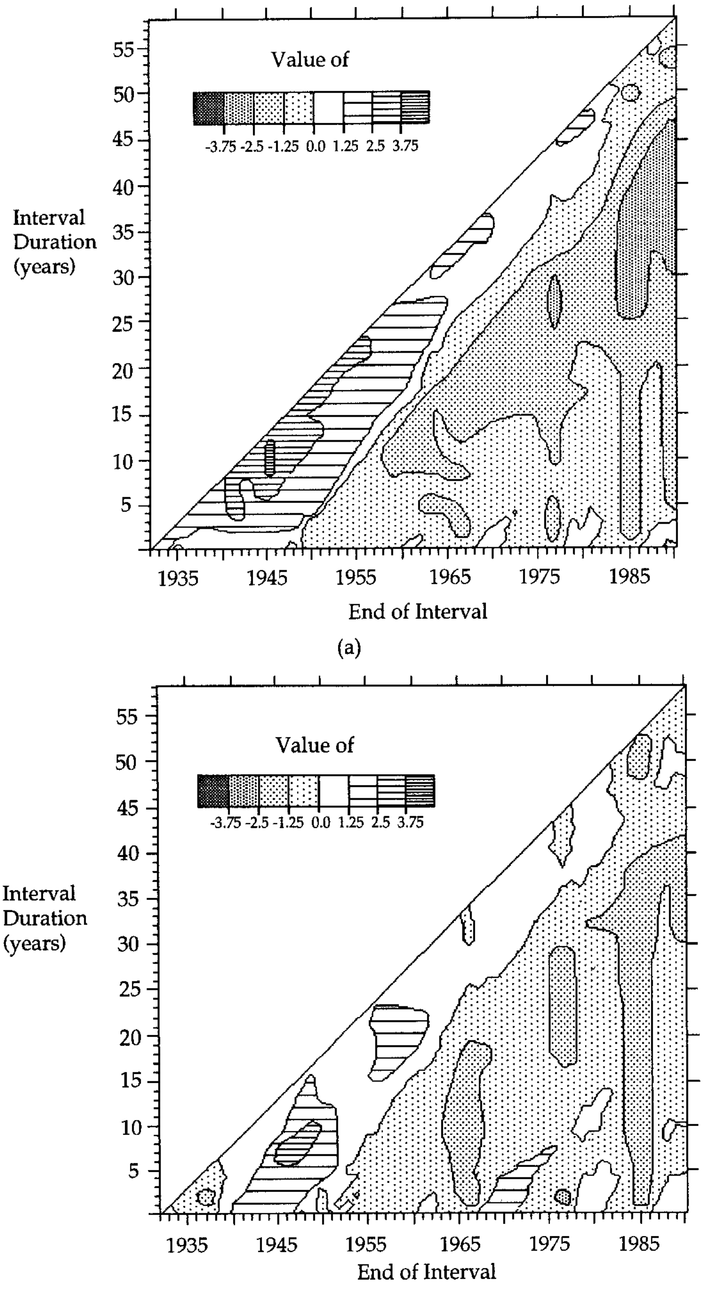


FIG. 5. (a) The $\beta$-statistic (see text) evaluated for earthquakes with catalog magnitudes of 5.0 or greater and mapped for all yearly time intervals ending between 1933 and 1990. The only statistically significant variation in the rate of seismicity ( $\beta \geq 3.74$) is for the 8 to 11-year intervals ending in 1946. (b) The $\beta$-statistic (see text) evaluated for earthquakes with newly determined magnitudes of 5.0 or greater and mapped for all yearly time intervals ending between 1933 and 1990. No statistically significant variation in the rate of seismicity ( $\beta \geq 3.74$) is found.

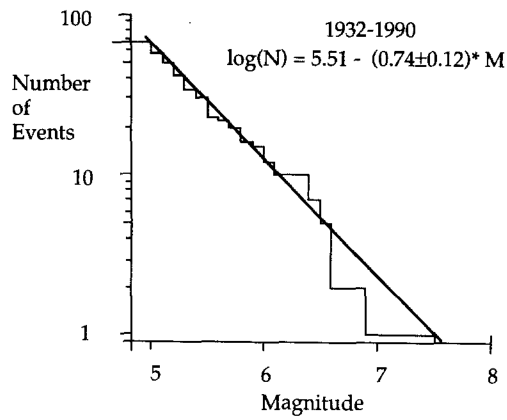


FIG. 6. The cumulative number of earthquakes with a magnitude of 5.0 or greater recorded in central part of the Southern California Seismic Network from 1932 to 1991 as a function of magnitude.

TABLE 4
POISSIONIAN PROBABILITIES OF LARGE EARTHQUAKES IN SOUTHERN CALIFORNIA

| Magnitude | $T_{avg}$ (yr) | Prob (in 10 yr) | Prob (in 30 yr) |
|---|---|---|---|
| 6.0 | $5 \pm 1$ | $86 \pm 3\%$ | $99.7 \pm .2\%$ |
| 6.5 | $12 \pm 3$ | $56 \pm 9\%$ | $91 \pm 5\%$ |
| 7.0 | $28 \pm 9$ | $30 \pm 9\%$ | $65 \pm 14\%$ |
| 7.5 | $67 \pm 30$ | $14 \pm 9\%$ | $37 \pm 14\%$ |
| 8.0 | $156 \pm 75$ | $06 \pm 6\%$ | $18 \pm 9\%$ |

fault in the next 30 years to be 60%. Our Poissionian estimate of the probability of an $M \geqq 7.5$ earthquake in any 30 years is 37%. The Poissionian estimate is for an earthquake on any fault in southern California, but it is clear from geology that a significant percentage of the largest earthquakes will be occurring on the San Andreas fault. The conditional probabilities should be higher than the Poissionian probabilities, as they included the information that it has been 300 years since the last major earthquake on the southernmost San Andreas fault. The agreement between the two types of probability is thus reasonable and shows that the conditional probabilities are only twice the Poissionian estimates.

Reliable magnitudes for smaller earthquakes would give us a better chance of recognizing significant changes in the rate of seismicity because more data would be available. It is possible that the increase in the early 1940s could be significant at a lower magnitude level; however, because it ends in 1946, we see no obvious correlation with the 1952 Kern County earthquake. To increase the usefulness of the data from the Southern California Seismographic Network, we plan to enter all the early phase data into the computer over the next few years. Based on this study, we believe that the Wood–Anderson amplitudes in the archive from 1944 to the present are reasonably accurate. Once the amplitude data for smaller earthquakes are entered into the data base, we can recalculate the magnitudes using the current routine procedures and the station corrections determined here and obtain reasonably consistent magnitudes from 1944 to the present. Prior to 1944, we would need to reread the amplitudes to obtain consistent reliable magnitudes.

## CONCLUSIONS

The local magnitude scale as used in southern California has changed over time. The methods for both reading the amplitudes and calculating the magnitude from a suite of readings appear to have evolved. The largest, single source of change is that amplitudes read before 1944 (Fig. 2) are systematically overestimated by an average of 15% compared to current reading procedures. These too large amplitudes led to significant overestimation of local magnitudes at least in the range $M_L$ 4.5 and up prior to 1944. Nine events were assigned a magnitude $M \geqq 5.0$ between 1935 and 1946 that by current procedure would be given a magnitude below 5.0. Using these unstable catalog magnitudes, several researchers had concluded that the rate of seismicity in southern California was higher before the 1952 Kern County earthquake. This study has shown that the apparent increase was an artifact of the change in method for reading amplitudes. The change from human to computerized estimation of event magnitude from a suite of amplitudes in 1975 also produced an artificial change in recorded magnitudes with magnitudes before 1975 higher by an average of 0.07 units. After recomputation of the magnitudes using uniform procedures throughout the catalog, the time period from 1940 to 1946 still has a higher seismicity rate, but at a statistically insignificant level. This rate of earthquakes predicts on average, an $M \geqq 6$ earthquake every 5 years, an $M \geqq 7$ event every 29 years, and an $M \geqq 8$ great earthquake every 156 years.

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